Transactions of the Korean Nuclear Society Autumn Meeting
Pyeongchang, Korea, October 30-31, 2014

Experimental Study on the Lift-off Phenomena of Bubbles Generated on Horizontal Tube

Sung Uk Ryu[a*], Seok Kim[a] and Dong-Jin Euh[a]
[a]*Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yuseong, Daejeon, 305-353*
[*]*Corresponding author: rsu@kaeri.re.kr*

1. Introduction

The heat transfer model for nucleate boiling on non-horizontal surfaces, such as a vertical surface and a horizontal tube, is different with the model on horizontal surfaces because the sliding bubble mechanism plays an important role. According to Sateesh et al. [1], the model for boiling on non-horizontal surfaces should consider microlayer evaporation and transient conduction owing to the sliding of bubbles, as shown in Eq. (1).

$$q_{tot} = (q_{me}+q_{tc})x_{st} + (q_{mes}+q_{tcs})x_s + q_{nc}, \qquad (1)$$

where q_{tot} is the total heat flux, q_{me} and q_{tc} are the microlayer evaporation and transient conduction heat flux from a stationary bubble, q_{mes} and q_{tcs} are the microlayer evaporation and transient conduction heat flux owing to the sliding bubbles, q_{nc} is the natural convection heat flux, x_{st} and x_s are constants determined by the area ratio parameter R defined as the ratio of area available per nucleation site to the projected area of the bubble at departure.

In a model of wall heat flux partitioning, the microlayer evaporation from sliding bubbles q_{mes} can be defined by four sub-models, i.e., the bubble departure diameter d_{d}, bubble lift-off diameter d_{l}, bubble departure frequency f, and active nucleation site density n_{b}, as shown in Eq. (2)

$$q_{\mathrm{mes}} = \frac{1}{6}\pi\left({d_{\mathrm{l}}}^3 - {d_{\mathrm{d}}}^3\right)\rho_{\mathrm{g}} h_{\mathrm{fg}} n_{\mathrm{b}} f, \qquad (2)$$

where ρ_g is density of the vapour, and h_{fg} is the specific latent heat.

Among these sub-models, this paper focuses on the bubble lift-off diameter. Situ et al. [2] stated that the bubble lift-off diameter, which is the bubble size when a bubble detaches from the heater surface, can be different from the bubble departure size, which is the bubble size when a bubble detaches from the nucleation site.

There have been a number of works performed on the departure and lift-off diameters of the bubbles generated on non-horizontal surfaces: Schomann [3], Luke and Gonfleo [4], Luke [5] (study on the horizontal tube) Cornwell and Schuller [6], Situ et al. [2], and Cho et al. [7] (study on the vertical surface).

Although there are many useful models to predict the departure and lift-off diameters of the bubbles generated on non-horizontal surfaces, the previous researchers did not deal with the bubble lift-off diameter model applicable on a horizontal tube. The boiling phenomena on the outside a horizontal tube is widely seen in many applications. Therefore, the objective of this research is to study the bubble lift-off size generated on a horizontal tube in a natural convective boiling flow. This study was carried out experimentally.

2. Experiments and Results

In this section, the experimental methods and results are suggested and analyzed.

2.1 Experimental setup and conditions

Figure 1 shows the experimental setup used to visualize the bubble growth and lift-off phenomena in pool boiling conditions. By inserting a single heater rod inside a pool, the test section was designed for measurement of bubble departure and lift-off size. The length and width of the pool are 300 mm and 60 mm, respectively. And the height of the pool is 400 mm. The test section to be observed in the direction of the front transparency made of polycarbonate. The test section to be observed in the direction of the front transparency is made of Pyrex glass (3 mm thickness). The horizontal heater rod of 3/4” diameter is installed at the h=85 mm vertical position. The length of the heater rod inserted into the water pool is 160 mm. Except for the 10 mm length of the non-heating portion of the rod, the length of the heating portion is actually 150 mm. The thermal capacity of the heater rod is about 2 kW. The heater power is determined by measuring the voltage and current applied to the heater rod. The left side and bottom of the water pool are made of a stainless steel plate of 20 mm in thickness.

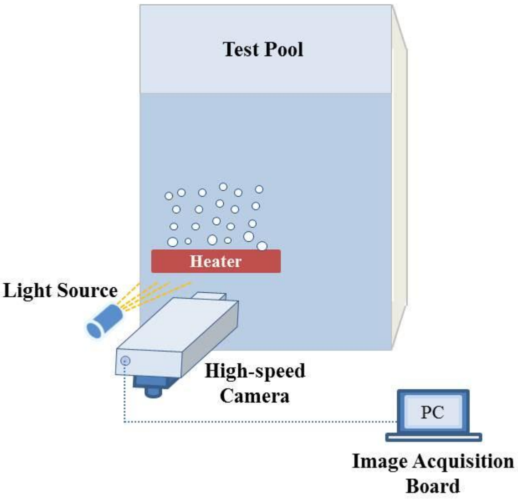


Figure 1 Experimental setup

To observe the departure and sliding behavior of the bubbles on the surface of the heated rod, the digital images were taken using a high-speed video camera. The camera frame rate was set as high as 2000 frame/s and the exposure time was 490 μs. The resolution of images was 800×600 pixels, which corresponds to a 42.1×31.6 mm window in reality. In this case, the distance between adjacent pixels is 52.6 μm.

A visi-size program was used to calculate the bubble size and analyze the digital images. The bubble size of the captured images was calculated by taking photos of a reticle with known diameters. Figure 2 shows a reticle map for reference size measurement.

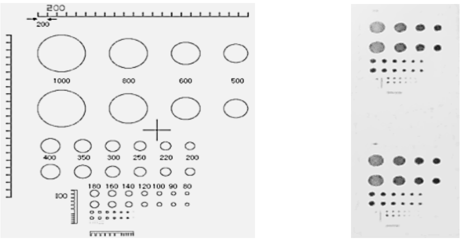


Figure 2 Reticle for reference size measurement (unit: μm)

The size of the bubbles measured in the present experiment ranged from 0.63 mm to 5.13 mm.

To measure the surrounding water temperature, the test section has six k-type thermocouples installed inside a pool. The maximum uncertainty of the thermocouple was expected to be 1.1 ℃ at the operation conditions.

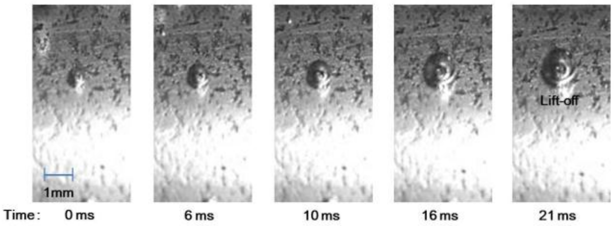
2.2 Results

The measured bubble departure and lift-off diameters, d_d and d_l are listed in Table 1.

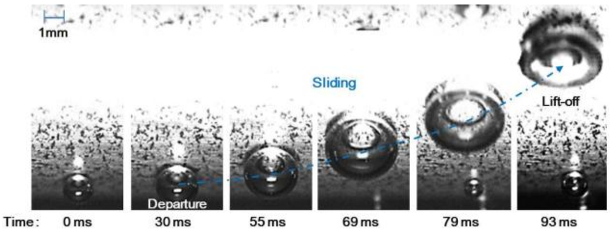
Figure 2 shows typical consecutive images of a bubble generated on the upper surface ($0° < \varphi_d$) and lower surface ($\varphi_d < 0°$) of a tube. The bubbles generated on the upper surface lift-off at the nucleation site and do not slide. On the other hand, the bubbles generated on the lower surface slide for some time and then lift-off at the position different with the nucleation site. Figure 4 shows the variation of bubble lift-off diameter against the departure diameter. The open and closed symbols express the diameter of the bubbles generated on the upper and lower surface of tube, respectively. As can be seen in this figure, the lift-off diameter of the bubbles generated on the upper surface of tube is similar with the departure diameter. On the other hand, the lift-off diameter of the bubbles generated on the lower surface appeared bigger compared to the departure diameter. This tendency becomes significant with the bigger bubbles generated near the bottom. The difference in the phenomena occurring at the upper and lower surface is due to the buoyancy force. There are three forces related to the bubble lift-off, which are the buoyancy force, unsteady drag force, and shear lift force (Situ et al.[2], Cho et al.[7], and Ryu et al.[8]) Among these forces, the effect of the buoyancy force is different depending on the position of the tube. The buoyancy force acts in the direction to promote the bubble lift-off on the upper surface, while suppressing it on the lower surface. Owing to this effect, it is much easier to lift-off on the upper surface than the lower surface.

Table 1 Measured bubble departure and lift-off diameters

φ_d [°]	d_d [mm]	φ_l [°]	d_l [mm]
2.22	1.41	2.22	1.41
9.76	1.21	9.76	1.21
24.31	1.56	24.31	1.56
25.23	1.51	25.23	1.51
25.84	1.53	25.84	1.53
29.92	1.53	29.92	1.53
36.22	1.83	36.22	1.83
36.91	1.67	36.91	1.67
37.25	1.69	37.25	1.69
44.99	1.71	44.99	1.71
46.18	1.70	46.18	1.70
49.49	1.58	49.49	1.58
51.67	1.56	51.67	1.56
53.97	1.73	53.97	1.73
54.92	1.65	54.92	1.65
57.41	1.71	57.41	1.71
61.22	1.47	61.22	1.47
62.39	1.78	62.39	1.78
68.38	1.88	68.38	1.88
69.14	1.47	69.14	1.47
-12.59	0.63	0.66	0.88
-13.61	0.75	0.99	1.49
-18.74	0.84	-0.33	1.65
-26.59	1.11	1.64	2.16
-44.88	1.33	0.00	2.61
-46.29	1.36	-2.30	2.60
-65.79	2.19	0.33	3.65
-69.23	3.18	0.33	5.13
-70.17	2.53	-0.99	4.29



(a) Bubble generated on the upper surface ($0° < \varphi_d$)



(b) Bubble generated on the lower surface ($\varphi_d < 0°$)

Figure 3 Consecutive images of bubble sliding

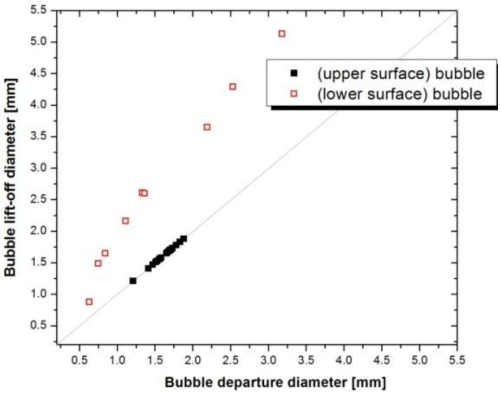


Figure 4 Variation of bubble lift-off diameter against the departure diameter

3. Conclusions

The growth and lift-off phenomena of bubbles generated on a horizontal tube were studied experimentally, and the results are summarized as follows:

- The lift-off diameter of the bubbles generated on the lower surface appeared to be bigger compared to the departure diameter, whereas the lift-off and departure diameter are similar in the case of the upper surface. This phenomenon is due to the buoyancy force acting in the direction to promote the bubble lift-off on the upper surface, while suppressing it on the lower surface.

ACKNOWLEDGEMENTS

This work is supported by the National Research Foundation of Korea (NRF- 2012M2A8A4004176) grant funded by Ministry of Science, ICT and Future Planning of the Korea government.

REFERENCES

[1] G. Sateesh, S.K. Das, A. R. Balakrishnan, “Analysis of pool boiling heat transfer: effect of bubbles sliding on the heating surface,” Int. J. Heat Mass Transfer, Vol. 48, 2005, pp. 1543–1553.

[2] R. Situ, T. Hibiki, M. Ishii, M. Mori, “Bubble lift-off size in forced convective subcooled boiling flow”, Int. J. Heat Mass Transfer, Vol. 48, 2005, pp. 5536–5548.

[3] H. Schömann, A. Luke, D. Gorenflo, “Size distribution of active nucleation sites with pool boiling heat transfer at single tubes with different roughness,” in:Proc. 10th Int. Heat Transfer Conf., Brighton, vol. 5, 1994, pp. 63–74.

[4] A. Luke, D. Gorenflo, “Heat transfer and size distribution of active nucleation sites in boiling propane outside a tube,” Int. J. Therm. Sci. Vol. 39, 2000, pp. 919–930.

[5] A. Luke, “Interaction between active and potential nucleation sites in pool boiling,” in: Proc. 4th European Thermal Sciences Conf., Birmingham, UK, 2004.

[6] K. Cornwell, R.B. Schuller, “A study of boiling outside a tube bundle using high speed photography,” Int. J. Heat Mass Transfer, Vol. 25, 1982, pp. 683–690.

[7] Y. J. Cho, S. B. Yum, J. H. Lee, G. C. Park, “Development of bubble departure and lift-off diameter models in low heat flux and low flow velocity conditions,” Int. J. Heat Mass Transfer, Vol. 54, 2011, pp. 3234-3244.

[8] S. U. Ryu, S. Kim, D. J. Euh, “Development of Lift-off Diameter Model of Bubbles Generated on Horizontal Tube,” 2014 ASME International Congress and Exposition, CANADA, 2014, accepted.